Effects of overstorey mortality on snow accumulation and ablation – Phase 2

Pat Teti

Mountain Pine Beetle working paper 2009-15

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Abstract

Pine-dominated forests in British Columbia are changing due to the current mountain pine beetle epidemic and to salvage harvesting operations. This is resulting in mature pine-leading forests being converted to a patchwork of cut blocks, plantations, and deteriorating beetle-killed stands. Hydrologic changes are therefore expected in watersheds dominated by lodgepole pine due to these natural and human disturbances. This project documents stand structure and snow hydrology in both healthy and beetle-attacked pine stands of different ages over a large geographic area. Snow storage and ablation rates in treed plots were compared with recent clearcuts to standardize data. The ratios of snow ablation rates in treed plots to those in adjacent clearcuts (snow ablation ratio) were proportional to plot-average solar radiation transmittance over a wide variety of lodgepole pine stands and geography. No similarly universal relation was found for snow storage at the start of the main ablation season, possibly because varying winter weather conditions confounded studies of the forest canopy and net snow accumulation. This project assists in the development of process-based hydrologic models by providing stand-level data on the structure and snow hydrology of growing and deteriorating pine stands at different post-disturbance ages. This will help watershed modellers improve the accuracy of hydrologic predictions under different forest disturbance scenarios.

Key words: mountain pine beetle, solar radiation transmittance, watershed hydrology, snow ablation, aerial photography, canopy photography

Résumé

En Colombie-Britannique, les forêts à prédominance de pins subissent des transformations en raison de l'infestation par le dendroctone du pin ponderosa et des travaux liés aux coupes de récupération. Cela ce traduit en forêts composées principalement de pins matures étant converties en mosaïques constituées de parcelles coupées, de plantations et de peuplements victimes du dendroctone en cours de détérioration. Des changements hydrologiques sont donc attendus dans les bassins hydrographiques de prépondérance de pin tordu à cause de ces perturbations naturelles et humaines. Le présent projet fournit des données sur la structure du peuplement et l'hydrologie hivernale des plantations à différents stades de récupération et sur les peuplements victimes du dendroctone à différents stades de détérioration et de récupération sur une vaste région géographique. L'accumulation de neige et les taux d'ablation nivale sur des terrains boisés ont été comparés aux récentes coupes à blanc afin de normaliser les données. Les proportions des taux d'ablation nivale sur des terrains boisées à ceux de coupes à blanc adjacents (proportion d'ablation nivale) variaient en fonction de la transmission du rayonnement solaire moyenne de la parcelle, sur une grande variété de pins tordus et une grande zone géographique. Aucune relation universelle similaire n'a été découverte pour l'accumulation de neige au début de la saison principale d'ablation, peut-être à cause des variations de la météorologie hivernale entre les zones d'études qui ont confondu les relations entre la couverture forestière et l'accumulation nette de neige. Ce projet aide à l'élaboration de modèles fondés sur les processus hydrologiques en fournissant des données à l'échelle des peuplements sur la structure et l'hydrologie de la neige de la croissance et de la détérioration des peuplements de pins à différentes périodes après perturbation. Cela aidera les modélisateurs des bassins versants à améliorer l'exactitude des prévisions de changements hydrologiques sous différents régimes de perturbation des forêts.

Mots clés: dendroctone du pin ponderosa, transmission du rayonnement solaire, hydrologie des bassins versants, ablation nivale, photographie aérienne, photographie de la couverture

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1 Introduction

Pine-dominated forests in B.C. are changing rapidly due to mountain pine beetle (MPB) infestation and salvage logging, with large expected consequences on stand- and landscape-scale hydrology. The beetle epidemic will result in patchworks of recovering plantations and killed stands across many watersheds. In the first phase of the project, a network of plots in natural (deteriorating) and managed (mostly recovering) pine stands were established, plot characteristics were documented, and one year of snow data were collected. In the second phase, snow monitoring was carried out for two additional seasons and plot characteristics were further sampled to document rates of change in stand structure due to the growth and deterioration of trees.

Watershed modeling is one of the few methods for predicting the combined effects of pine beetles and logging over large watersheds but this requires stand-level data on the snow hydrology of plantations and killed stands at different times after disturbance. This project is helping fill that information gap.

In the aftermath of the current MPB infestation, most formerly mature pine stands have suffered a high percentage of overstorey mortality. Therefore, in order to predict the marginal effect of salvaging versus retaining killed pine stands, we need to do so in comparison with attacked, but unlogged, stands rather than in comparison with mature, healthy stands which has been common in the past. This project is the first attempt to compare snow hydrology changes over time in plantations versus killed stands.

The broad objectives were to document snow storage, snow ablation rates, and stand structure in a network of pine stands representing a wide variety of natural and managed stands over a large geographic area. Extension objectives were to make the results known to forest managers, licensees, and scientists through workshop presentations, publications, and websites.

More specific objectives included the sharing of raw data with project participants and the development of semi-quantitative guidelines to help managers minimize hydrologic risks and/or uncertainty while planning pine salvage operations.

2 Materials and Methods

2.1 Plot establishment

Five new study areas (Baker, Moffat, Rosita, Taseko, and Vanderhoof) were established during phase 1 of this project as described in Teti (2008). Data from the Mayson study area was included in phase 1 of this project but Mayson Lake was not included as part of phase 2. This report describes the work done up through phase 2 that was not included in the previous report, and summarizes combined results for phases 1 and 2.

2.2 Snow surveys

In 2006 and 2007, snow storage and ablation rates were determined by a single detailed ground snow survey followed by aerial surveys. In 2008, snow was repeatedly surveyed on the ground in order to better estimate snow water equivalent (SWE) and ablation rates using methods previously described (Teti 2008).

2.3 Tree surveys

Vegetation surveys were conducted in the summer of 2007 in all 24 treed plots in the five study areas. In each plot, trees were surveyed in four circular sub-plots of either 50 or 200 m^2, depending on the estimated stem density. All stems taller than 1.3 m were categorized by species and crown condition. Tree crowns were categorized as green, green-red, red, red-grey, grey, and snag. In addition to the stem counts, a sample of up to 20 trees between 2 and 4 cm diameter at breast height (DBH) and up to 20 trees greater than 4 cm DBH was measured (the first 10 green trees and up to 10 red trees) in each circular plot. If a tree had a DBH greater than 2 cm, its height and DBH were recorded. If DBH was greater than 4 cm, additional measurements included height to base of functional crown and crown diameter. Crown diameter was estimated along north-south and east-west lines by visually projecting crown perimeters down to the ground. Grey trees and snags were not measured. Stand ages as of 2005 were obtained from the British Columbia Ministry of Forests and Range Vegetation Resources Inventory (VRI) with the exception of plot TON whose VRI age of 68 was changed to 130 after counting rings in cores from two representative canopy-forming trees. Killed stands were defined as those having more than 50% of stems dead at the time of the surveys.

2.4 Coarse woody debris surveys

In the summer of 2006, coarse woody debris was surveyed on 26 of the 29 plots using methods similar to those of Densmore et al. (2004). Within each 50 x 50 m plot, four transects of 35.4 m were set up in the cardinal directions and centred on the plot as shown in Figure 1. Along each transect, data were collected on each piece of woody debris if it met these criteria: at least 5 cm diameter, at least 5 cm vertical relief above the forest floor, and its axis forming an angle of less than 45 degrees from the horizontal. For each piece, distance along transect, diameter, height above the forest floor, direction of fall, and decay class were recorded. Stumps and stems were tabulated separately. Volume and pieces per unit area were summarized by ecoclassification, stand age, and height above ground.

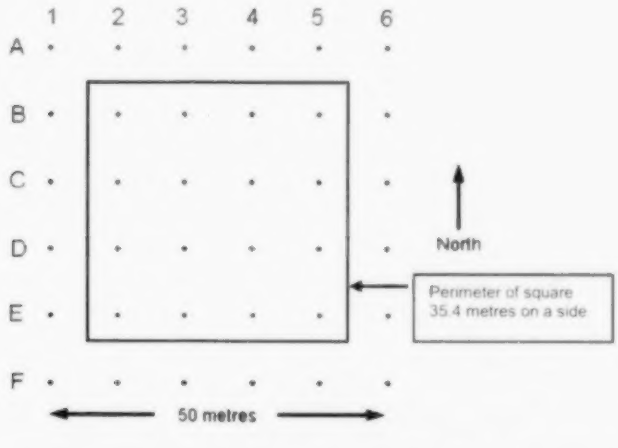

Figure 1. Line-intercept sampling design for coarse woody debris.

2.5 Canopy photography and light parameters

Hemispherical canopy photos were taken at each of 36 points in all treed plots in 2006 and were repeated in 2008 to document changes due to growth of live trees and deterioration of dead trees.

In clearcuts, photos were taken only at a subset of points and only in 2006. Photos were analyzed for canopy density and canopy gap (gap = 1 – density) in two different coordinate spaces, one based on polar coordinates and the other based on sun position as a function of time of day and time of year. The former was for the calculation of diffuse radiation transmittance, sky view factor, and canopy gap within different zenith angles. The latter was for calculation of direct radiation transmittance. Field and analytical methods are described in detail in Teti (2008). The same parameters were calculated independently from photos taken in 2006 and 2008, thus allowing changes in plot averages to be determined.

2.6 Repeated vertical aerial photography

Vertical aerial photos of all plots were taken from fixed-wing aircraft on different dates between March 2006 and March 2009. The original purpose of the aerial photography was to estimate the dates of snow disappearance in the first phase of the study (2006 and 2007). However, it was also discovered that aerial photos taken when there is complete snow cover on the ground and an overcast sky provide a unique view of trees, allowing interpretations of forest structure that are not possible on conventional aerial photos. These photos were used to document defoliation, blowdown, and crown diameter growth over time, and to estimate canopy gap for comparison with results from ground-based hemispherical photography.

2.7 Oblique aerial photography

Helicopter-based oblique aerial photos were taken of some plots in 2008 and 2009 to test the feasibility, accuracy, and possible cost-effectiveness of estimating the percentage of solar radiation transmitted at the plot-scale by remote sensing.

2.8 Stand parameters and parameter relationships

Table 1 is a conceptual model of site and stand characteristics with the most independent variables in the first column and the snow hydrology parameters in the last column. Although climate, weather, and soils are some of the most independent variables, only time since disturbance and disturbance type (logging or beetle-kill) are represented in this project. The stand structure parameters in columns 2 and 3 depend on those in column 1 but they control those in column 4, which are the snow parameters of interest. Parameters in solid boxes were quantified in some way for this project and those in bold text were used to develop empirical relationships. It is useful to explore relations among parameters in the first three columns because this reinforces the connectedness between the fields of forest ecology, forest mensuration, and forest hydrology. Ultimately, the most important relationships for this project are those that improve our ability to predict snow accumulation and ablation rates as functions of variables in columns 1 to 3. More specific definitions and rationales for parameter selection follow.

Table 1. Conceptual model of site and stand characteristics and their relationships.

Increasingly dependent variables →			
Most independent variables	**Stand characteristics**	**Mass and energy transfer regulators**	**Snow hydrology parameters**
Time since disturbance	**Tree height, crown diameter, and depth**	**Solar radiation transmittance**	**Snow storage**
Disturbance type	**Basal area**	**Canopy gap fraction**	**Snow ablation rate**
(Climate)	Stems per hectare	Sky view factor	
(Weather)	Coarse woody debris volume and spatial distribution	Aerodynamic roughness	
(Soils)	Surface area of leaves and stems (LAI)		

2.9 Snow parameters

The parameter used to compare snow storage between plots was snow water equivalent (SWE) at the beginning of the sustained ablation period (the *active melt period* of Faria et al. 2000) because this is the amount available for rapid spring melt. If maximum SWE occurs before the start of the main ablation period, the difference could be due to vaporization, which in young juvenile stands and clearcuts could be as much as 1 mm/day on many winter days (Bernier 1990; Bernier and Swanson 1993). Therefore, SWE at the start of the main ablation period has a larger effect on spring runoff generation than does absolute maximum SWE that might have occurred weeks earlier. In the years 2006 and 2007, a single snow survey was done in each plot just before the main ablation period and the dates of snow disappearance were estimated from aerial surveys, thus providing a two-point SWE time series for each plot. The dates on which to do ground surveys were based on weekly reconnaissance snow surveys near each study area. The second point on the SWE curves in 2006 and 2007 were estimated by sequential aerial photography at approximately weekly intervals based on the assumption that plot average SWE was rapidly approaching zero when half of the ground was snow-free. In 2008, SWE time series were estimated from six ground snow surveys of all plots.

2.10 Tree survey parameters

Raw data from tree surveys were used to estimate percent species composition; percentage of trees in the green, red, grey, and snag categories; basal area of green and red stems; volume of green and red crowns per unit area; and the crown footprint of green and red crowns. Basal area and other metrics of grey stems were not calculated because grey trees were not measured.

3 Results

3.1 Snow storage and ablation rates

In most years and most plots, the main ablation period started in mid to late March and ended in mid to late April. Snow water equivalents varied considerably between plots, between study areas, and between years, ranging from 43 mm in a mature grey-attacked stand in 2006 in the Rosita study area to 311 mm in the clearcut in 2007 at the Baker study area. Average ablation rates ranged from 1.2 mm per day in the 30-year-old plantation at the Moffat study area in 2008 to 7.0 mm per day in the clearcut at the Rosita study area in 2008. Table 2 summarizes selected stand structure parameters, SWEs, and ablation rates in 2006 through 2008. Since the purpose of this project is to investigate the effects of stand characteristics on SWE and ablation rate rather than the effects of differences between study areas or years, SWE and ablation rate in each plot were divided by SWE and ablation rate in the nearby clearcut to get a *SWE ratio* and an *ablation ratio* for each year. These were averaged over the three years to get an average SWE ratio and an average ablation ratio for each treed plot. Snow water equivalent ratios and ablation ratios in clearcuts are equal to 1 by definition.

Average SWE ratios in the 24 treed plots ranged from 54% to 130% and average ablation ratios ranged from 46% to 111%. In the Baker study area, average SWE ratios in treed plots had a smaller range of 54% to 82%, indicating that all treed plots had lower SWE than the clearcut. In the Vanderhoof study area, treed plots had small ranges in both SWE ratios (78% to 91%) and ablation ratios (55% to 70%). At Rosita, SWE ratios in treed plots averaged 76% to 111%, with only the 12-year-old plantation having a higher average SWE ratio than the clearcut. Ablation ratios in the treed plots at Rosita ranged from only 60% to 78%. The Moffat study area was unusual in that SWEs in three of the treed plots were, on average, greater than SWE in the clearcut. Plot MO1, a mature pine stand that was attacked by beetles in 2005 and which lost most of its needles before April 2007 (Figure 16 in Teti 2008), had an average of 30% higher SWE but a 19% lower ablation rate than the Moffat clearcut. Plot MRC1, a 10-year-old plantation, was the only treed plot in the project that had a higher average ablation rate than the nearby clearcut.

Table 2. Summary of plot level data.

												2006		2007		2008			
Study Area	Plot Name	Age (1)	Age (2)	Height (3)	SPH (4)	Dead (5)	BA, R-G (6)	Gap (7)	SVF 06 (8)	T 06 (9)	T 08 (10)	SWE (11)	Abl Rate (12)	SWE (11)	Abl Rate (12)	SWE (11)	Abl Rate (12)	Avg SWE Ratio (13)	Avg Abl Ratio (14)
Baker	BCC	2	2	0	0	NA	0.0	92%	82%	82%		152	5.6	311	5.7	179	6.7	1.00	1.00
	BOD1	216	3	15	1312	69%	14.2	61%	32%	31%	30%	97	2.9	194	3.5	122	4.6	0.65	0.61
	BOD3	211	3	15	550	75%	6.2	74%	45%	42%	43%	108	4.0	172	4.0	99	4.6	0.60	0.70
	BON	126	126	14	4103	47%	30.8	41%	18%	15%	23%	79	2.1	169	3.1	99	3.5	0.54	0.48
	BRC1	8	8	4	1312	0%	4.5	96%	85%	90%	73%	123	4.6	214	5.0	110	5.1	0.70	0.82
	BRC2	33	33	10	1025	40%	14.1	57%	32%	32%	39%	103	3.0	174	3.2	108	4.8	0.61	0.61
	BYN	126	2	14	3853	77%	13.4	61%	31%	31%	31%	126	4.7	191	3.5	131	5.2	0.72	0.74
Moffat	MCC	2	2	0	0	NA	0.0	100%	98%	100%		90	4.1	101	5.6	136	5.9	1.00	1.00
	MO1	128	3	17	2237	79%	8.9	61%	33%	31%	39%	83	3.8	182	6.5	160	2.0	1.30	0.81
	MO3	128	3	21	1774	73%	12.4	57%	29%	28%	41%	79	3.6	127	3.6	139	4.7	1.05	0.77
	MRC1	10	10	0	0	NA	0.2	100%	96%	99%	94%	107	7.1	118	5.4	154	3.6	1.16	1.11
	MRC2	29	29	10	1537	36%	18.7	48%	26%	23%	26%	53	2.4	116	3.3	118	1.2	0.87	0.46
Rosita	RCC	2	2	0.0	0	NA	0.0	100%	95%	93%		55	6.9	147	4.0	117	7.0	1.00	1.00
	ROD1	199	25	8.0	2099	13%	18.7	69%	45%	45%	43%	57	3.8	125	2.8	104	3.8	0.92	0.60
	ROD2	213	25	5.0	1687	4%	11.2	77%	57%	57%	56%	66	4.4	134	3.6	90	2.9	0.96	0.65
	RON	213	2	15.5	1425	70%	17.2	65%	41%	38%	41%	43	5.4	98	2.6	96	3.7	0.76	0.65
	RRC1	12	12	3.3	325	4%	2.1	96%	86%	90%	74%	81	5.4	150	4.0	100	3.7	1.11	0.78
	RYN2	44	44	6.2	8847	3%	26.4	60%	36%	41%	27%	62	4.1	112	3.0	85	4.1	0.87	0.65
Taseko	TCC	2	2	0.0	0	NA	0.0	100%	98%	99%		M	M	M	M	M	M	M	M
	TOD2	138	3-25	12.2	500	61%	10.1	64%	32%	40%	41%	M	M	M	M	M	M	M	M
	TOD3	158	3	12.4	337	73%	8.5	63%	38%	55%	42%	M	M	M	M	M	M	M	M
	TON	130	130	7.4	1525	36%	16.0	63%	35%	32%	40%	M	M	M	M	M	M	M	M
	TRC1	16	16	3.1	225	0%	0.5	96%	91%	94%	88%	M	M	M	M	M	M	M	M
	TYN	68.0	68	7.3	7648	0.4	31.9	58%	30%	21%	25%	M	M	M	M	M	M	M	M
Vanderhoof	VCC	2	2	0.0	0	NA	0.0	100%	99%	100%		103	7.9	272	6.6	158	5.7	1.00	1.00
	VOD1	135	135	7.3	1387	47%	5.0	56%	33%	28%	37%	67	2.3	209	4.5	149	4.7	0.79	0.60
	VOD2	135	5	11.8	1687	84%	5.0	67%	39%	40%	31%	104	3.6	214	5.2	150	4.9	0.91	0.70
	VRC1	13	13	4.6	1500	2%	5.8	81%	56%	62%	56%	88	4.4	211	6.2	137	3.4	0.83	0.70
	VYN	75	75	10.0	7648	23%	28.7	42%	21%	18%	25%	90	3.1	187	3.2	123	4.3	0.78	0.55

Key to Table 2 columns:

1) In years, as of 2005.

2) Years since logging or attack. TOD2 had evidence of multiple episodes.

3) Avg. height, m, green to red stems only, with DBH greater than 4 cm.

4) Stems/ha, all types, green to snag, greater than 4 cm DBH.

5) Number of dead stems greater than 4 cm DBH/Total stems.

6) Basal area in sq.m/ha, green to red stems only, with DBH greater than 4 cm.

7) Plot average gap fraction in 30 degree zenith angle from fisheye photos (2006).

8) Sky view factor in 2006.

3.2 Canopy characteristics from hemispherical canopy photos

The phase I report described the methods by which optical canopy characteristics and solar radiation transmittance were estimated and summarized results from the 2006 photography. Very high correlations were found between the plot averages of diffuse transmittance and total transmittance, and between the plot averages of sky view factor and total transmittance. Both r-squared values were equal to 0.98, indicating that diffuse transmittance, total transmittance, and sky view factor contained very similar information about pine stands represented in this project.

The phase I report also documented differences in the variability of radiation transmittance within and between plots. Transmittance was highly heteroskedastic between plots, one of the implications of which was that the number of unbiased points required to estimate plot average solar radiation transmittance to within an accuracy of 5% transmittance ranged from less than 6 to more than 70 between plots. However, in this project the number of points sampled in the five main study areas was constant at 36. Therefore, the confidence limits on plot average radiation transmittance differed between plots, ranging from less than 1% transmittance to 8% transmittance.

The highest within-plot variability was found in plantations where crowns were starting to merge and in old stands having a wide variety of tree ages due to complex disturbance histories (Teti 2008). Variability was low in plots with the lowest and highest average transmittances as shown in Figure 2. This is because the population bounds are 0 and 1, meaning that if the sample mean approaches either zero or 1, the sample variance must approach zero.

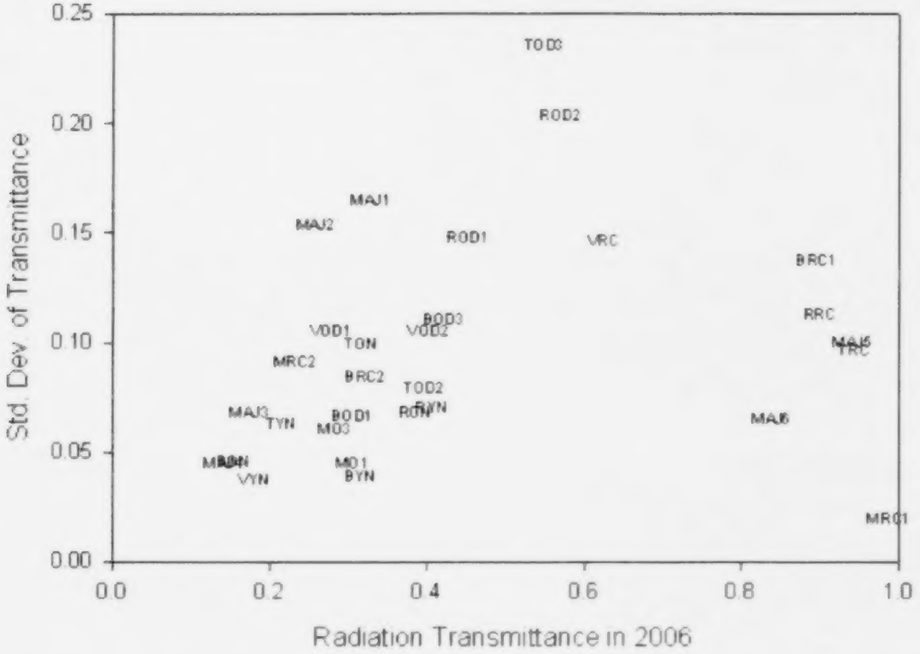

Figure 2. Standard deviation of transmittance versus average radiation transmittance.

3.3 Snow storage versus stand structure

Average SWE ratios were regressed against plot average values of crown volume per unit area, square root of basal area, and canopy gap in a 30 degree zenith angle. When all plots were analyzed together, there were no statistically significant relations between SWE ratio and stand structure. However, there were positive correlations between SWE ratio and canopy gap in three study areas when study areas were analyzed separately as shown in Figure 3. Similar results were found in regressions between SWE ratios and the square root of basal area. The r^2 values between SWE ratios and canopy gap at the Baker, Moffat, Rosita, and Vanderhoof study areas were 0.49, 0.04, 0.69, 0.70, respectively, while those between SWE ratios and square root of basal area were 0.75, 0.05, 0.49, and 0.63, respectively.

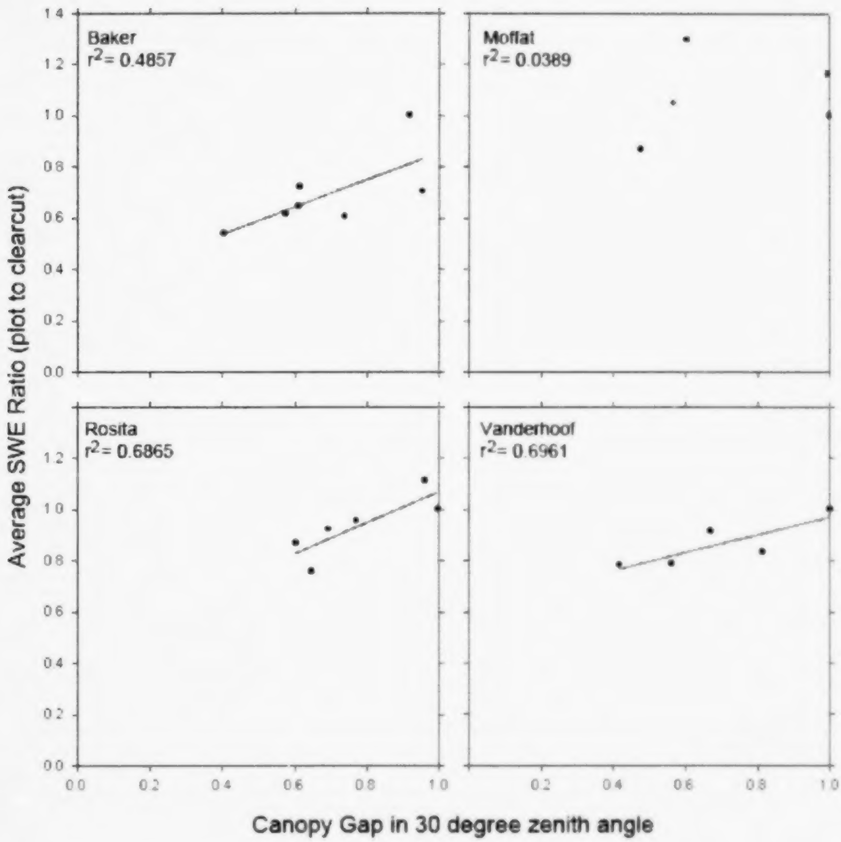

Figure 3. Average SWE ratios versus canopy gap in each study area.

3.4 Snow ablation versus stand structure

Average ablation ratios were regressed against crown volume per unit area, basal area, and solar radiation transmittance. There were good correlations between ablation ratios and stand structure parameters when all study areas were grouped together. Ablation ratios in all plots were highly correlated with both radiation transmittance (r^2 = 0.8040) and the square root of basal area (r^2 = 0.7875) as shown in Figure 4. Since the data were standardized using SWEs and ablation rates in clearcuts, the data points for the clearcuts could be regarded as biased. With the clearcut data removed, the r^2 values for average ablation ratios versus transmittance and the square root of basal area were 0.6362 and 0.6038 respectively. This suggests that plot average radiation transmittance and the square root of basal area contain similar information about stand structure, even though only the basal area of green to red trees was used in the basal area calculation.

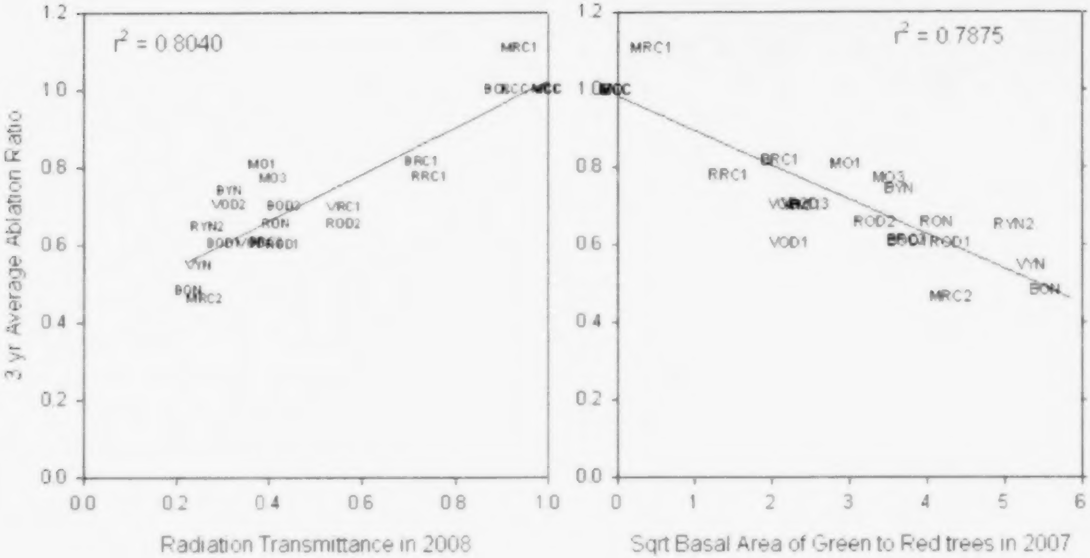

Figure 4. Average ablation ratios vs plot average radiation transmittance and square root of basal area.

3.5 Changes in stand structure over time

In this sample of plots, stand structure parameters derived from hemispherical photos (e.g. diffuse radiation transmittance, total radiation transmittance, sky view factor, and angular canopy gap) are highly correlated with one another, that radiation transmittance decreases with plantation age, and that it could take about 75 years for sites disturbed by wildfire to reach the level of radiation recovery achieved by plantations in 30 years (Teti 2008). These conclusions regarding changes over time are based on a classic substitution of space for time (Morrison et al. 2008) which is necessary for short-term studies. However, due to relatively rapid changes that are occurring in these stands, this study also documents changes in the structure of individual plots over time by repeated ground-based canopy photography and aerial photography.

Hemispherical canopy photos were taken in all plots in 2006 and were repeated in all treed plots of the five main study areas in 2008. Figure 5 is a scattergram of plot average transmittances in 2008 versus those in 2006. Points above the y=x line indicate increases in transmittance while those below the line indicate decreases. Increases suggest net deterioration while decreases suggest net growth.

The plot with the most obvious net deterioration during the monitoring period was MO1. Aerial photos taken in April 2006 and April 2007 (Fig. 16 in Teti 2008) reveal a dramatic change in tree crowns from yellowish-green to grey, indicating that trees in the plot had been attacked in the summer of 2005 and were mostly defoliated in the winter of 2006/07. None of the other mature pine stands showed as much visible change in structure during the monitoring period as plot MO1. A stem map based on the aerial photos indicated that 67% of the canopy-forming trees had turned from green to grey in that one-year period, an unusually rapid rate of needle drop.

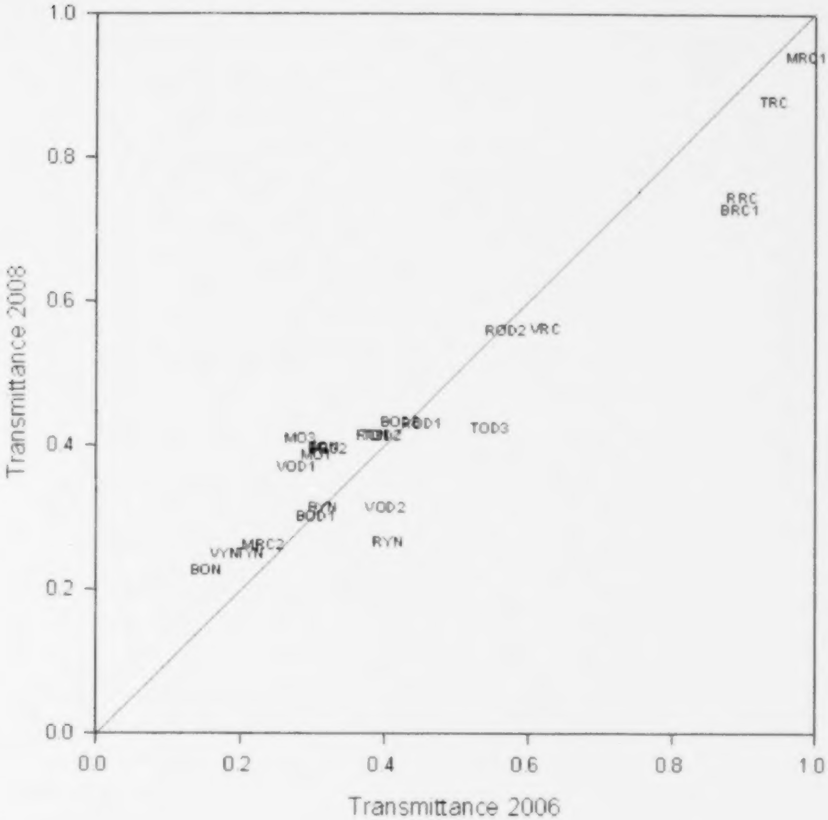

Figure 5. Plot average solar radiation transmittances in 2008 versus 2006.

This agrees well with the 2007 vegetation survey in which an estimated 79% of stems greater than 4 cm DBH were dead. Calculated radiation transmittances in MO1 increased from 31% in 2006 to 39% in 2008. Inspection of hemispherical photos taken at the same ground locations in those two years confirmed that the binarized versions of the photos represented the actual crown conditions in the two years reasonably well and that the calculated canopy data should be accepted. Figure 6 is an example of a pair of canopy photos taken at the same point in plot MO1 in those two years.

The plantations provide good examples of changes in stand structure that would be expected. The plantations less than 20 years after logging were growing rapidly while the two oldest ones (29 and 33 years since logging as of 2005) were becoming defoliated during the project due to beetle-attack. Differences in the health of young versus old plantations are evident in the 2007 tree surveys and on aerial photos taken between 2006 and 2009. The plantations BRC2 and MRC2 had mortalities of 40% and 36%, respectively (in stems greater than 4 cm DBH) at the time of the 2007 vegetation surveys. Their radiation transmittances were estimated to have changed by +7 and +5 percentage points respectively between 2006 and 2008 as indicated by their plotting positions above the y=x line in Figure 5. In contrast, the five younger plantations had no beetle-attack, exhibited vigorous growth, and had decreases in radiation transmittance of −3 to −17 transmittance percentage points in two years. Figure 7 is a pair of binarized hemispherical photos taken at a typical point in plot BRC1 in 2006 and 2008. The growth of individual tree crowns and

branches is clearly visible as expansion of silhouettes from the outside to the inside of the hemispherical photos.

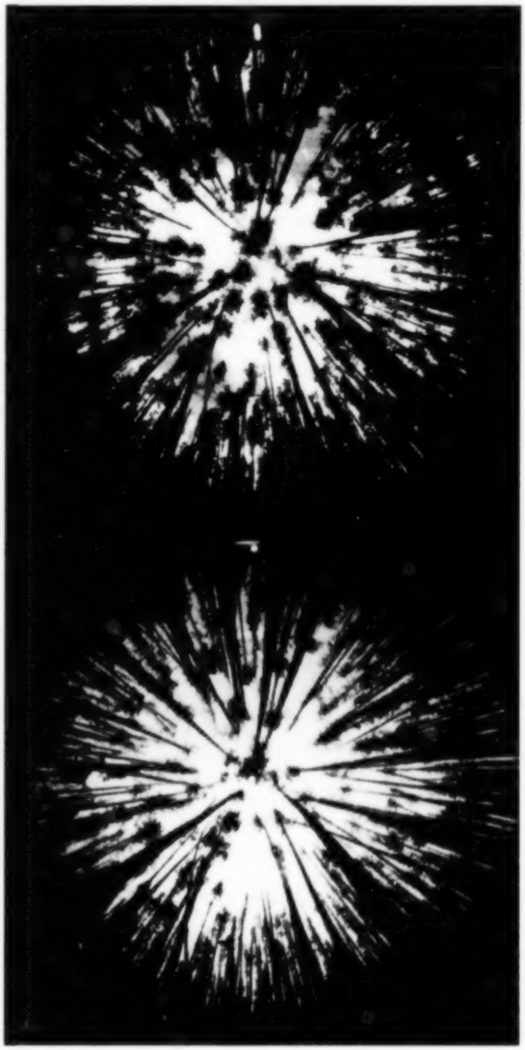

Figure 6. Hemispherical canopy photos taken at point B1 in plot MO1 in May 2006 and June 2008. This plot was beetle-attacked the summer of 2005 and at least 67% of the trees were defoliated by the time the second photo was taken. Radiation transmittances at this point were 35% and 41% in the two years while plot average transmittances were 31% and 39%.

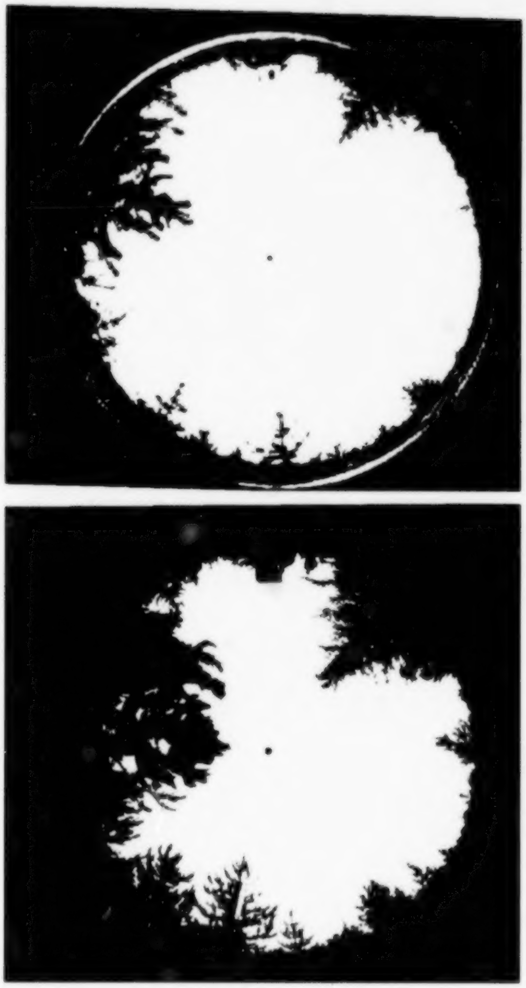

Figure 7. Hemispherical canopy photos taken at point C5 in plot BRC1 in 2006 and 2008. North is at the top. The cutblock was logged between 1991 and 1997; in 2007, average height of stems with DBH greater than 4 cm was 3.9 m. Plot average radiation transmittances in 2006 and 2008 were 90% and 73%.

Transmittances in plantations measured in 2006 and 2008 are shown in Figure 8 and are plotted versus years since logging. Plots that were photographed in both years have two points on the graph thus defining changes over time as indicated by arrows. This figure also shows the general relationship for transmittances versus age in 2006 before BRC2 and MRC2 were attacked. We would expect radiation transmittance in individual healthy plantations to decrease over time with a slope similar to the overall relationship (an average of 2 percentage points per year). The healthy plantations (BRC1, MRC1, RRC1, TRC1, and VRC1) did, in fact, have transmittances that decreased at similar rates as the overall trend of transmittance versus age but the attacked plantations had increasing transmittances. This reflects net deterioration more like the beetle-attacked mature plot MO1 than the non-beetle-attacked plantations.

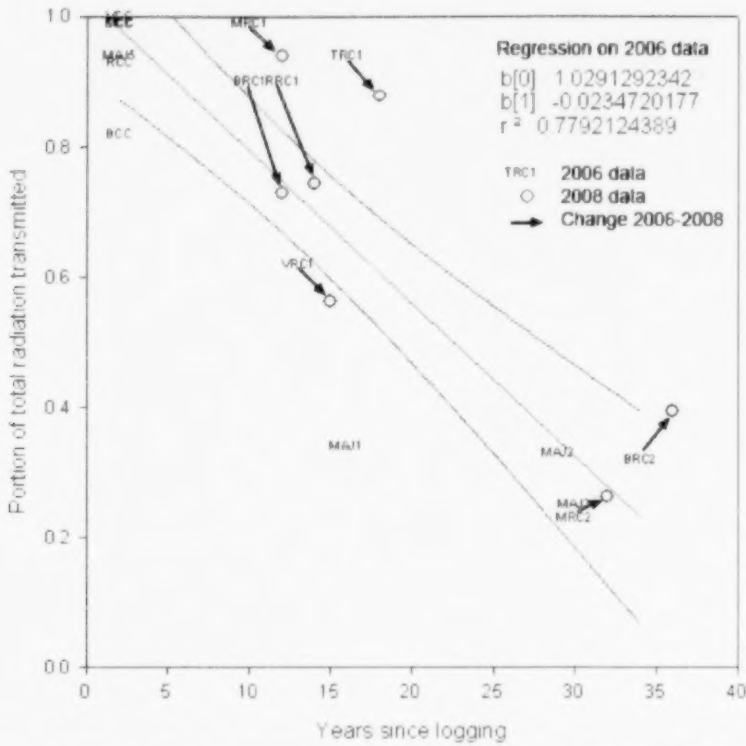

Figure 8. Radiation transmittances in plantations over time. Arrows indicate changes in plots that were re-photographed in 2008.

Figure 8 and the linear regression of 2006 data in Figure 8 include the data points for clearcuts. Due to the presence of trees on the south sides of plots RCC and BCC, those two plots had lower transmittances than would be typical of clearcuts. Therefore, the regression in Figure 8 is also likely biased. A more accurate relationship of transmittance versus time in plantations would show the effects of a regeneration delay during which transmittance measured at a height of about 1 m remains at 100% for five to 10 years, after which it decreases rapidly. This would be more accurately represented by removing the clearcut points from the regression relationship.

In phase 2, differences in stand structure and snow hydrology between plantations and killed stands were examined as functions of time since disturbance to compare killed pine stands retained on the landscape to salvage logged stands, as discussed below.

3.6 Marginal effects of salvaging versus retaining grey pine stands

Plantations and killed stands change as dead trees deteriorate and live trees grow. Changes and the differences between plantations and killed stands are hypothesized to be reflected in measurable stand structure parameters, snow accumulation, and snow ablation rates. The marginal effects of salvage logging on snow hydrology at time t can be expressed as the ratio between snow storage or ablation rate in a plantation and that in a killed stand after t years, e.g.

$$SWE_{plantation,tc} / SWE_{killed\ stand,tk} \qquad \text{or} \qquad \text{Ablation rate}_{plantation,tc} / \text{Ablation rate}_{killed\ stand,tk}$$

where tc = time since clearcutting and tk = time since the stand was killed.

The most powerful way to detect these differences would be to measure SWEs and ablation rates in adjacent plantations and killed stands with replication over a number of years. However, the alternative method used in this project, substituting space for time, was to estimate SWE ratios and ablation ratios as functions of time for a sample of killed stand/clearcut pairs and the same parameters in a sample of plantation/clearcut pairs. Comparisons can then be made between regression lines rather than individual data points. By calculating standardized SWE ratios and ablation ratios, data can be combined from plots in different locations. The killed stands and plantations do not have to be near each other as long as each one is near a clearcut. This study provides such a set of data with six plantation/clearcut pairs and nine killed stand/plantation pairs.

The ages of beetle-killed stands in column 2 of Table 2 from the B.C. Ministry of Forests and Range VRI are the estimated stand ages before the infestation. For each of the nine plots which had been beetle-killed, the number of years since mortality was estimated from forest disturbance data fields in the VRI, from personal observation, and from beetle spread maps (http://cfs.nrcan.gc.ca/subsite/mpb/historical-historique). Figures 9a and 9b show SWE ratios and ablation ratios versus time for killed stands and plantations. Linear regression models and 95% confidence limits on regressions are shown. Because SWE ratios were correlated with gap fraction in three of the four study areas and ablation ratios were correlated with solar radiation transmittance in all study areas, those stand parameters were also plotted versus time and their regression lines and confidence limits calculated as shown in Figures 9c and 9d.

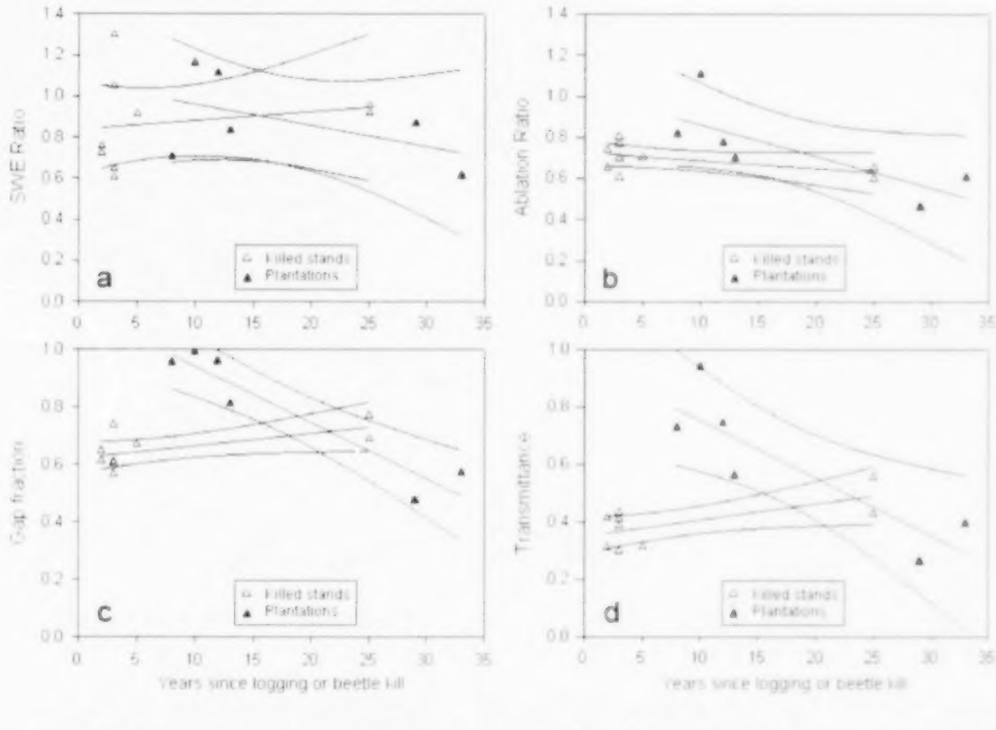

Figure 9. Plot average values of SWE ratios (a), ablation ratios (b), gap fractions (c), and solar radiation transmittances (d) versus time since logging or time since defoliation. Regression lines and 95% confidence intervals on regressions are shown.

4 Discussion

4.1 Stand structure parameters related to SWE and ablation rate

Previous studies have shown that stand structure parameters can explain significant portions of the variability in snow accumulation and ablation rates when the data are standardized to clearcuts. Winkler (2001) found that SWE ratios and ablation ratios were correlated with crown length, square root of crown volume, and crown closure. Her ablation ratios were also correlated with the square root of basal area. However, that was prior to the current beetle epidemic. Pine stands are more complex after the epidemic because the percentages of killed trees vary between stands and the characteristics of individual dead tree crowns vary, both within stands and for individual trees over time. However, Winkler's (2001) results also show that crown length, crown volume, crown area, and basal area contain largely redundant information. Of the field parameters, DBH (from which basal area is derived) is one of the most attractive for use in attacked stands as long as crown condition is also noted. Optically measured parameters are attractive because they do not require any judgments about crown condition.

Canopy gap in a 30-degree zenith angle was chosen as a predictor of SWE ratios because previous results (Teti 2003) indicated that it was an effective parameter for explaining plot average differences in snow storage. It also does not require a description of crown condition. An alternative would be Leaf Area Index (LAI) but it is highly correlated with optically measured canopy gap (or canopy density, e.g. Pomeroy et al. 2002) and is generally estimated by optical methods anyway. Radiation transmittance in early April under clear skies was chosen as a predictor of ablation ratios because 1) net radiation is the major source of snowmelt energy in openings, conifer stands, and defoliated stands (Spittlehouse and Winkler 2004; Thyer et al. 2004; Hardy et al. 1998); 2) the highest incoming radiation occurs on clear days; and 3) early April is the approximate mid-point of the main ablation period in these study areas. The selection of tree measurement parameters was more problematic. When the tree surveys were being planned, it was speculated that the crowns of defoliated trees would not affect SWE or ablation rates so defoliated trees were counted but not measured. Thus, in this study, the effects of defoliated pine trees are represented in the canopy gap and radiation measurements but not in the basal area measurements.

4.2 SWE ratios versus stand structure

In contrast with other studies (Winkler 2001; Talbot and Plamondon 2002), no stand structure parameter was found that could consistently explain stand average SWE ratio in this study. Neither canopy gap nor the square root of basal area could explain the majority of the variance in stand average SWE ratios when study areas were combined. This might have been because the canopy can produce confounding effects when winter weather differs between study areas, thus causing different periodic ablation conditions during the net accumulation season. It has been shown that the percentage of intercepted snow (Schmid and Gluns 1991) and its fate, i.e., unloading, melt, or vaporization (Pomeroy et al. 1998) vary with the weather. The fate of snow stored on the forest floor is equally subject to variable ablation processes during the net accumulation season if weather conditions are conducive. For example, low canopy density tends to allow more snow to accumulate during snowfall, but it can also result in more ground-level ablation between snowfalls, depending on wind speed, air temperature, humidity, and solar radiation (e.g. Bernier 1990; Bernier and Swanson 1993). Differences in winter weather between study areas could therefore be sufficient to explain inconsistent correlations between late winter SWE and canopy structure parameters. The same argument would apply to different correlations in one study area between years. The poor correlation between stand structure and net

accumulation in the Moffat plots suggests that that study area might be a good location to study complex wintertime accumulation and ablation processes.

4.3 Ablation ratios versus stand structure

Even with clearcut SWE ratios removed from Figure 3a, radiation transmittance in treed plots explained 64% of the variance in average ablation ratios across all study areas. The square root of basal area was similarly effective, suggesting that the processes by which canopy affects the main snow ablation event of the year are simpler than those by which it affects net snow accumulation. As a result, both radiation transmittance and basal area appear to be good indices of relative snow ablation rates in pine-leading treed stands having a wide variety of disturbance histories and structures on the B.C. Interior Plateau. The correlation between ablation ratios and stand structure is better than the correlation between SWE ratios and stand structure perhaps because the former reflects a more consistent role of the canopy in reducing solar radiation whereas the latter is the result of sometimes positive and sometimes negative effects of canopy on net accumulation in winter. During the net accumulation season, more gaps can allow more accumulation during snowstorms but they can also allow more ablation when the weather is conducive to vaporization and melt.

4.4 Stand structure and snow parameters *vs* time since disturbance

Figures 9c and 9d suggest that in these study areas, gap fraction and radiation transmittance in plantations and killed stands follow similar patterns of change versus time since disturbance. The regressions suggest that the values of those parameters in plantations cross the values in killed stands at 20 to 25 years. No such statements can be made about SWE ratios in plantations versus those in killed stands due to the high variability of SWE ratios (Figure 9a). This could be because stand structure can affect net SWE either positively and negatively depending on winter weather as discussed above.

The ability to discriminate ablation ratios versus time in plantations from those in killed stands is a little better as shown in Figure 9b. If one is willing to accept an alpha error probability greater than 5%, the regression lines (and the fact that ablation ratios in clearcuts equal 1 by definition) indicate that plantations have higher SWE ratios than killed stands for approximately 15 years and that they have lower SWE ratios than killed stands after 25 years. However, the small sample size and absence of plots in killed stands between the age of 5 and 25 years since attack means that the linear regression for killed stands in Figure 9b is very preliminary. The time required for dead stems to fall down and for killed stands to regenerate is expected to vary. Figures 9a through 9d show data for plantations and killed stands with approximately the same dates of disturbance. If salvage logging is done x years after a stand is killed, then the data for plantations would be shifted x years to the left in Figure 9.

This comparison of changes in the structure and snow hydrology of plantations versus retained grey stands should be regarded as a first approximation. Retained grey stands are problematic because the full range of possible changes is not represented in this sample. For example, a killed stand with a large amount of secondary structure and in which the dead trees remain standing for 20 years would likely be represented by points below the killed stand regression lines in Figure 9. On the other hand, killed stands with a longer regeneration delay and in which the dead stems blow down after a few years would be represented by points above the killed stand regression lines. However, considering climatic and biological uncertainty in the future, the full range of changes in plantations over time is also not represented in Figure 9. The methods described above provide a straightforward method by which new studies can add more data on attacked stands and plantations to these relationships in the future.

5 Conclusions

Average snow ablation ratios changed consistently with solar radiation transmittance and basal area across a wide variety of lodgepole pine stands and a large geographic area. No similarly universal relations were found between SWE at the beginning of the main ablation season and stand structure parameters. It is hypothesized that was due to interactions between canopy structure and different winter-time ablation conditions between study areas. This implies opportunities for more research on winter-time processes that affect net accumulation, especially in the Moffat study area.

There were consistent changes in the structure and snow hydrology of pine plantations after post-logging reforestation and after post-attack canopy mortality. The changes were positive in healthy plantations due to growth and negative in attacked plantations due to deterioration. Clearcuts and plantations are expected to produce faster snowmelt than severely-attacked pine stands for 15 years after logging. However, after 25 or 30 years, plantations should have slower snowmelt than killed pine stands that have developed naturally for that amount of time, assuming that the plantations do not have serious health problems. Although the rates of deterioration and recovery of killed stands vary more than is suggested by this small sample, the results should help watershed managers make forest planning decisions over periods of three decades or more.

The results point to a course by which future work could reduce uncertainty. One of the higher priorities is to measure SWE and ablation rates in killed stands approximately 10 to 20 years after disturbance and in nearby clearcuts. This would provide an improved sample of SWE and ablation ratios in killed stands and the results would be directly compatible with those reported herein.

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